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Computational study of the aerodynamics of the gliding snake Chrysopelea Paradisi

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Abstract — **Flying snakes exhibit an exceptional gliding mechanism without any added appendages that can aid gliding. Several studies on the mechanism have shown that the snake performs a ballistic dive from a height and glides through the air at high angles of attack of 35 degrees and above. Research has shown the morphing of their body structure from a cylindrical to a flattened shape with a rounder dorsal surface makes it possible for these creatures to not only perform glide but also various turning maneuvers. In this study, the variations of the lift, drag and normal force coefficients (C_L, C_D and C_N) with glide angle are predicted by solving the three dimensional, steady, viscous, incompressible flow over the snake during its glide using CFD study. The three dimensional CFD analysis shows that the lift and normal force coefficients keep increasing increases with the glide angle even up to a high glide angle of 35 degrees which helps the snake to counteract the gravitational force. Further, the aerodynamic efficiency of the snake is still less than its maximum value at this glide angle, which is not predicted by two-dimensional analysis. This study can aid in applications for security and defense.**

I. INTRODUCTION

Chrysopelea paradisi or more commonly called as the flying snake belonging to the Colubridae family consists of a group of five species with lengths of the order 0.6 – 1.2m [1], [2]. This is yet another inspiration for humans to experiment and implement designs from nature. These are mildly venomous and found over the regions of South-East Asia, Maluku, Philippines, Southernmost China, India and Sri Lanka [1], [2].

Chrysopelea, despite having an apparently disadvantageous design shows exceptional gliding ability. It is a typical snake containing no appendages, skin flaps, or any typical feature of a flying animal [2]. The snake uses it entire body as a flattened surface, much like that of a wing throughout its aerial locomotion. In addition, the snake constantly reconfigures its shape at different stages of the flight [1].

Understanding the aerodynamics of flying snake can find application in the sectors of homeland security, defense and military. Robots inspired by animals and other living beings have been built [3]. Snake-like robots have been built [4] which can move on land and water. In the aerospace industry, further studies can help in the development of biomimetic air vehicles which can aid in reconnaissance in densely forested hilly terrains.

Current research has helped to explain the aerodynamics behind the glide trajectory to a certain extent. The snake has a typical cylindrical body with an approximately circular cross-section when it is not in flight. During flight, it changes its profile by flattening its ventral surface such that it attains a configuration which is aerodynamically sound. The snake performs a jumping take-off from a higher altitude passing through a ballistic dive which has a steep glide path [1]. Once the velocity increases to a certain value, enough lift is generated to enable the snake to glide. This is achieved by alteration of the snake body cross-section dorsi-ventrally over the range of its trajectory. The analysis of the flying snake also helps us to explore into the realm of aerodynamics of morphed structures.

Miklasz et al. [5] started the wind tunnel testing of stationary models which were simple geometry of the cross-section of the snake. The Reynolds number for the experiment was 15,000 and measurements of lift and drag at various angles of attack were obtained. Further studies were performed in a water tunnel with Reynolds number in the range if 3000-15000 using time-resolved digital particle image velocimetry. Studies conducted on the snakes by Socha [1] showed the capability of one of the species to perform aerial maneuvers like turning and targeting. However the mechanisms that the snake does to perform the maneuvers remain unknown.

A detailed analysis has been performed in recent times on the glide trajectory of the snake. Theoretical analysis of pitch stability during gliding in flying snakes done by Anush Krishnan et al. [2] examined the stability in the longitudinal direction of the flight by introducing two dimensional models.

In the current study, a two-dimensional flow visualization of the cross-section of the snake's body available in [2] is taken and unsteady two dimensional visualization of the flow is performed using Autodesk Flow Design [6] at various angles of attack. This is done to get an insight into any interesting flow patterns attributable to the cross-sectional shape of the snake. Further, steady three dimensional flow over the gliding snake is done to visualize and make interesting observations. This is performed in Ansys Fluent [7].

II. METHODOLOGY

Autodesk Flow Design runs a transient, incompressible flow solver that employs a Finite Volume Method [8] solver. Turbulence is solved for using a Smagorinsky Large Eddy Simulation (LES) model [9]. It is run on a Windows 7 Home Premium Operating System on a machine equipped with a 4 GB RAM and Intel Core i5-2450M CPU which runs at 2.50 GHz.

For the analysis of three dimensional flow, Ansys Fluent, version 14.0 [7]was employed on a computer with Windows 8.1 Operating System with 6 GB RAM, 2 GB Nvidia GeForce GT 740M graphics card and Intel Core i5-3230M CPU at 2.60 GHz. Spalart – Allmaras turbulence model [10] is used to calculate the flow parameters. SIMPLE scheme [11] is used to solving the flow.

A. Two dimensional model

The cross-section of the snake is approximated as a rounded – triangle with fore – aft symmetry and flapped at the leading and trailing edges. To visualize the transient features of flow over the two dimensional profile, Autodesk Flow Design [6] is used. The velocity contours over the cross-section for different angles of attack were obtained. The Reynolds number used is 3000, which is based on the chord length of the cross-section and a glide velocity of 10 ms^{-1}.

B. Three dimensional model

The study has been extended to the flow visualization of three dimensional model of the snake. The same cross-section used in two dimensional flow visualization [2] is used here. The body shape of the snake has been assumed to be S-shaped with varying thickness from head to tail with the same cross-sectional shape without twist. The analysis is done at different angles of attack. The model is an approximated structure of the snake, with its head and small portion of the tail removed for simplicity. This approximation is not expected to greatly affect the accuracy of the solution.

The average chord length of cross-sections is chosen as 5cm and the length of the snake is assumed to be 1m. The body is placed in a domain with dimensions [28m X 18m X 18m].

The characteristic fluid used is air at standard temperature and pressure conditions. Reynolds number of the flow based on the body length and a free-stream velocity of 5 ms^{-1} is 300000.

The glide angle of the snake is varied from 0, 20 and 35 degrees. The mesh has 38,548 nodes with 2,23,426 elements. Fig. 1 shows a view of the grid on snake's surface.

III. RESULTS AND OBSERVATIONS

A. Two-dimentional cross-section flow visualization

The angle of attack on the snake model during gliding is increased from 0 to 50 degrees at an interval of 5 degrees in the two-dimensional flow analysis. The Von Karman vortex street is clearly observed in the downstream of the flow for angles of attack greater than 20 degrees. Fig 2 shows velocity contours for representative angles of attack 4 seconds after the initialization.

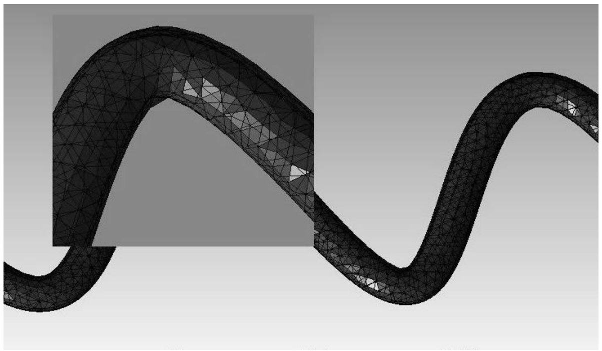

Fig. 1. Close up view of mesh on snake's surface.

B. Flow analysis of three dimensional model of the snake

The glide angle was varied from zero to 35 degrees for this analysis. Table I shows the variation of coefficients of lift and drag with glide angle obtained from the three dimensional analysis. Also the coefficient of normal force, C_N is calculated from (1).

$$C_N = C_L \cos\gamma + C_D \sin\gamma \qquad (1)$$

where γ is the glide angle.

TABLE I. VARIATION OF COEFFICIENTS OF LIFT AND DRAG WITH GLIDE ANGLE.

γ (Deg.)	**Parameters**		
	C_L	***C_D***	***C_N***
0	0.1187	1.7877	0.1187
20	0.8180	1.8451	1.3996
35	1.3206	1.8322	2.1322

Table II gives the details of times to attain a convergence of four orders in the residuals for the above angles of attack.

An increase in the values of coefficients of lift and normal force with glide angle was observed as expected. The drag coefficient exhibited a non-monotonic behavior in the range tested. The effective C_L/C_D increases with increase in glide angle in the tested range.

Table II. Convergence Criteria and Time of Convergence.

γ (Deg.)	***Number of iterations***	***Time taken for convergence (seconds)***
0	1506	2720
20	1842	3584
35	2011	4811

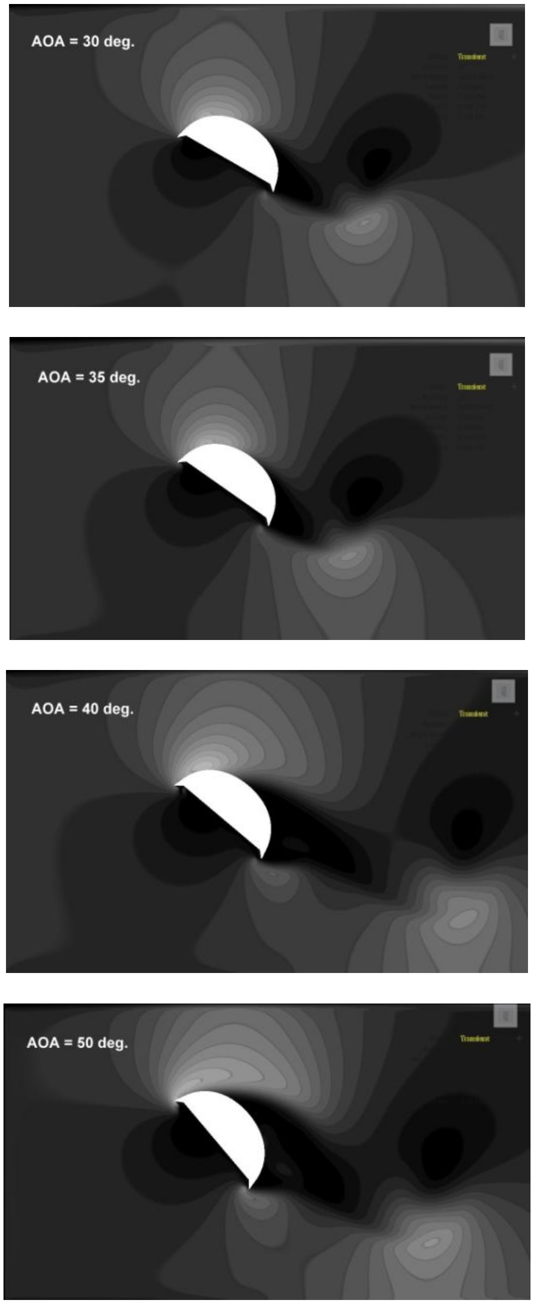

Fig. 2. Velocity distribution of two dimensional cross-section with various angles of attack 4 seconds after initialization.

IV. DISCUSSIONS

A. *Two-dimentional flow*

The flow accelerates on the dorsal surface and faces adverse pressure gradient condition in the downstream region which causes flow reversal and formation of vortices. At angles of attack less than 20 degrees the flow the wake region is weak hence flow separation is not prominent. As we increase the glide angle, Von Karman Vortex Street is observed. The size of the vortex formed at the trailing is observed to increase with increase in angle of attack. Fig. 3 shows the developed Von Karman street.

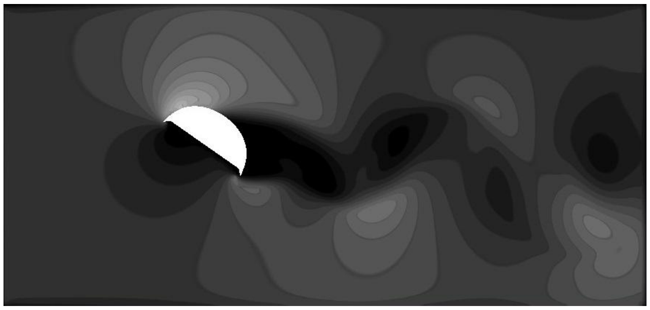

Fig. 3. Fully developed Von Karman vortex street.

Further, as observed in [2] at 35 degree angle of attack, there is a formation of secondary vortex from the leading edge on the dorsal surface. Additional suction can explain the enhancement in lift of the model.

At low angles of attack, the flow fairly remains attached to the dorsal and ventral surfaces and hence the wake region formed is insignificant. The size of the Von Karman Street observed is small. As angle of attack is increased we observe that the size of the Von Karman Street increases.

At 40 degrees angle of attack, flow separation was observed. At high angles of attack of the two dimensional model, a vortex formation in addition to the Von Karman vortex street is observed at the leading edge on the posterior side of the cross-section.

The results obtained are similar to those obtained in [2].

B. *Three dimensional flow*

As observed in Section III, we can deduce that the snake geometry produces higher lift at higher angles of glide. Coefficient of drag is found to increase up to 20 degrees. Thereafter a reduction in C_D value is observed which effectively increases the Aerodynamic Efficiency (C_L/C_D). Also C_N, which counteracts the gravity is increasing even at 35 degrees angles of glide as seen from Table I.

TABLE III. VARIATION IN AERODYNAMIC EFFICIENCY WITH GLIDE ANGLES.

Γ (Deg.)	C_L/C_D
0	0.066
20	0.443
35	0.720

From Table III, it can be observed that the maximum value of aerodynamic efficiency is not reached even at a glide angle of 35 degrees. This probably explains the reason why snakes prefer to glide down at higher angles.

V. CONCLUSIONS AND FUTURE WORK

Two dimensional unsteady flow and three dimensional steady flow over a flying snake was studied during its glide using CFD.

Socha et al. [1] in their two dimensional analysis have observed that C_D increases with increase in angle of attack. Our two dimensional results confirm the observation of [2]. However the three dimensional flow analysis in this work showed a nonlinear variation in C_D versus angle of glide where C_D monotonically increased up to 20 degrees. Thereafter a reduction in C_D value is observed which effectively increases the Aerodynamic Efficiency (C_L/C_D). Also C_N, which counteracts the gravity is increasing even at 35 degrees glide angle. Convergence for angle of glide of 40 degrees was not obtained as the solution was oscillating. This needs further study.

This work can be extended to unsteady three dimensional flows with twisted body structures that morph with time. This may throw light on more interesting facets into the glide mechanism of the flying snake which could help us in advancing the boundaries of biomimetics [12] and investigate the possibilities for flying snake-like aerial vehicles.

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